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APPLICATIONS

Design of a twin capacitive load and its application to the outdoor rating of photovoltaic modules

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ABSTRACT

This paper describes the design of an original twin capacitive load that is able of tracing simultaneously the *I–V* characteristics of two photovoltaic modules. Besides, an example of the application of this dual system to the outdoor rating of photovoltaic modules is presented, whose results have shown a good degree of repeatability. Copyright © 2013 John Wiley & Sons, Ltd.

KEYWORDS

photovoltaic; *I–V* characteristic

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1. INTRODUCTION

Photovoltaic (PV) modules are rated under standard test conditions (STC), which are defined by a normal irradiance of 1000 W/m^2, a solar AM1.5 spectrum [1], and a cell temperature of 25°C. The usual rating procedure is made up of two steps. The first one consists of measuring the current–voltage (*I–V*) characteristic of the PV module [2] and, simultaneously, the magnitude of the operating conditions: irradiance and cell temperature. Second, the measured *I–V* characteristic is corrected to the STC using well-know procedures [3].

Manufacturers usually rate their modules at the factory using a flash as the light source, and whose results are set out in the "flash-report" of each PV module. Later, within the framework of purchasing procedures, the manufacturer rating may be verified on PV module samples [4,5]. This verification may be carried out on-site, which has some advantages. For example, it allows the characterization of the short and long-term power degradation of the modules [6,7] without the need to uninstall them and send them back to the laboratory. However, the on-site characterization of PV modules is not yet a common practice within the framework of quality control procedures, despite of the fact that published results of outdoor rating procedures are very positive in terms of both accuracy (closeness to the real value) and precision (repeatability) [4] [8].

Such outdoor rating procedures rely on using a reference PV module [9] (hereinafter called the reference) calibrated by an accredited laboratory, which should be of the same type as the modules being tested (hereinafter called the sample/s) in order to ensure that the spectral, optical, and thermal responses are very similar. In a simple way, these procedures consist of the following steps. First, the two *I–V* curves of the sample and the reference are traced quasi-simultaneously. Second, the operating conditions (irradiance and cell temperature) are calculated through the measured short-circuit current and the open-circuit voltage of the reference. Third, the *I–V* curves of both reference and sample are corrected to STC [3]. And finally, the deviations of the calculated parameters under STC of the reference regarding its calibration are calculated, and these same deviations are applied to the parameters of the sample in order to obtain its final rating under STC.

In practice, the two *I–V* characteristics are measured with a certain delay because common electronic loads are usually able to trace only one *I–V* curve at the same time. The recommended maximum interval between the sample and reference module measurements is 3 min [4]. Obviously, the lower this delay, the more stable the operating conditions are. But the main advantage of minimizing this delay is the substantial reduction of the testing time, which is especially important when a high number of samples must be measured.

This paper describes the design of an original twin capacitive load that is able of tracing two *I–V* characteristics simultaneously, which may reduce the testing time and the rating uncertainty. Besides, an example of application of this load is presented, which compares the outdoor rating of reference PV modules of different technologies regarding their actual calibration.

2. DESIGN OF THE TWIN CAPACITIVE LOAD

I–V tracers usually employ a capacitive load for measuring the curve of PV generators, specially, for high power levels. The principles of operation and the schematic designs of single capacitive loads have been described in the literature long time ago [10]. The power circuit of the twin capacitive load presented here is shown in Figure 1, which is just the duplication of the single capacitive load that has been described elsewhere by the authors [11]. This single load has been continuously improved after the experience of testing large PV generators of up to 500 kWp [12] within the framework of several rural electrification projects [13,14] and large grid-connected power plants [15].

The functions of the components of the power circuit, whose values are given in the Appendix, are the following:

(i) Insulated gate bipolar transistors (IGBT) 1 and 2 are switched on–off sequentially for charging and discharging, respectively, the capacitor C. The size of this capacitor is selected according to the required charging time, whose recommended value is between 50 and 200 ms [16] in order to avoid the capacitance effects of the PV module (faster charging times) and the variation of operating conditions during the tests (slower charging times). Assuming a PV module with a fill factor of unity, it is easy to find that the charging time, t_C, is given by [10]:

$$t_C = \frac{V_{OC}}{I_{SC}} C \qquad (1)$$

where V_{OC} and I_{SC} are, respectively, the open-circuit voltage and the short-circuit current of the PV module. In practice, the actual charging time is slightly higher than the value given by the previous equation because the fill factor is lower than unity. In any case, the charging time depends on the capacitor size, and on the ratio V_{OC}/I_{SC}, which depends, for his part, on the number of solar cells connected in series/parallel and on the operating conditions (irradiance and cell temperature).Table I displays the ranges of the ratio V_{OC}/I_{SC} for different technologies under STC, which have been obtained from a recent survey of commercial PV modules [17], and the calculated ranges for C assuming Equation (1) and $t_C = 100$ ms. Needless to say, the capacitor must be selected with a nominal voltage, V_{NOM}, higher than the maximum expected value of V_{OC}. We normally use two different electrolytic capacitors depending on the PV technology: $C = 22$ mF/$V_{NOM} = 63$ V (enough for most x-Si and CdTe modules) and $C = 4.7$ mF/$V_{NOM} = 160$ V (enough for most a-Si modules). In any case, the size of these capacitors should be adapted to the characteristics of each PV technology. In particular, thin film modules may require higher charging times (capacitor sizes) than the previous presented values.

(ii) Diode D_1 protects the load against the reverse polarity connection of the PV module.

(iii) The negative precharging circuit (marked with the dotted line) applies a negative voltage (−9 V) to the capacitor, which allows the voltage drop across the load to be compensated. This ensures that the *I–V* characteristic starts in the second quadrant ($V < 0$ and $I > 0$) and crosses the short-circuit point ($V = 0$, $I = I_{SC}$) [2].

(iv) The fuse F_1 protects the IGBT2 against the direct connection of the PV module, which may occur in the case of an eventual failure of the IGBT1.

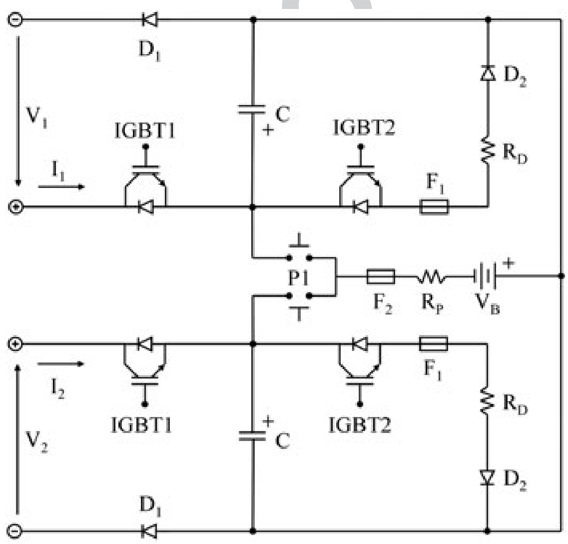

Figure 1. Power circuit of the twin capacitive load. IGBT, insulated gate bipolar transistors.

Table I. Ranges of the ratio V_{OC}/I_{SC} under STC of commercial PV modules whose nominal power is between 50 and 300 W_p and the approximated ranges for the capacitor size assuming a charging time of 100 ms.

Technology	V_{OC}/I_{SC} range (under STC) [Ω]	Maximum V_{OC} (under STC) [V]	C [mF]
Mono x-Si	3–12	64	8–33
Poly x-Si	2–22	80	5–50
a-Si single junction	60–120	140	1–2
μc-a-Si	18–144	174	1–10
Cd Te	19–34	61	3–5

STC, standard test conditions; PV, photovoltaic.

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(v) The resistor R_D allows the capacitor C to be discharged when the IGBT2 is switched on, which should be carried out before to trace a new *I–V* curve. During discharging, the capacitor voltage decreases exponentially from V_{OC} to zero with a time constant R_DC. The selection of R_D is a trade-off between a fast discharging with high power dissipation (low R_D) or a slower discharging with lower power dissipation (high R_D).

(vi) Finally, diode D_2 is used to avoid the discharge of the capacitor C through R_D and the diode of the IGBT2 when the negative precharging voltage has been applied.

The currents of the PV modules (I_1 and I_2) are measured with external calibrated resistors (±0.5% accuracy), which are not displayed in Figure 1, and the voltages (V_1 and V_2) are directly measured at the output terminal of the PV modules in order to carry out a "four-wire" measurement. For example, Figure 2 displays the current and voltage curves of two modules during the charge of the capacitors, which have been registered using a differential four-channel oscilloscope (±1% voltage accuracy).

Each one of the power circuits displayed in Figure 1 is driven by one control circuit whose layout is shown in Figure 3. This circuit has been improved on as regards the previous one [11] using a better debounce circuit (R_1-R_2-C_1 network plus inverter) and providing a safe optical insulation between the power and control circuits. The switch placed on the left-hand side of Figure 3 is used to select the charge (IGBT1) or the discharge (IGBT2) of the capacitor, and the push button switches on the selected IGBT (1 or 2) when it is pressed.

Finally, each control circuit is powered by the power supply displayed in Figure 4. The circuit is made up by three ~~DC/DC~~ converters connected to a rechargeable 12 V battery, which provide three outputs: one with +5 V for the supply of the debounce circuits and two with +15 V for the optocouplers. This supply circuit is designed to provide a safe isolation between the control and power circuits. On the one hand, the debounce circuit is optically isolated from the power circuit by means of the optocoupler (Figure 3). For this reason, the +5 V DC/DC does not provide any isolation, and its ground (0 V reference) is the same with that of the battery (GND0). On the other hand, the +15 V DC/DC converters certainly provide galvanic isolation between the IGBTs and the battery. Besides, the latter also ensures that the supply of one IGBT is isolated from the other, which prevents undesired connections in the power circuit. For example, if the grounds of both supplies (GND1 and GND2) are the same, the IGBT2 would be bypassed (Figure 3).

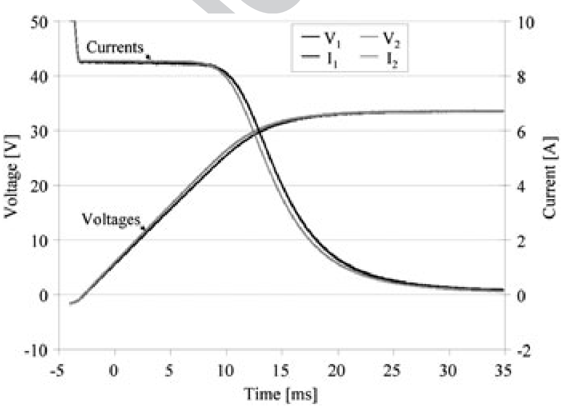

Figure 2. Current and voltage of two photovoltaic modules as a function of time, which have been registered during the charge of the capacitors using a differential four-channel oscilloscope.

3. EXAMPLE OF APPLICATION

In order to assess the performance of the twin capacitive load, an experiment has been carried out with four pairs of PV modules of different technologies that are shown in Table II. Each pair is made up of two calibrated references, but one of them has been considered the sample, which allows the outdoor rating results to be compared with its actual calibration.

The experiment consisted of the following sequence:

(i) The modules were installed on a static structure with tilted latitude (Conergy and Sharp) and on a one-axis azimuthal sun-tracker (Solon and Yingly), cleaned, and covered with a white insulation around 30 min before starting the register of the *I–V* characteristics.

(ii) One hour before midday, the modules were uncovered, and their *I–V* characteristics were registered at a periodicity of 1 min until the cell temperature was stabilized, which is assumed when the open-circuit voltage becomes constant. Hence, these measurements are performed under a nearly constant irradiance and a variable cell temperature, which ranges from the ambient temperature up to the stabilized value. These measurements are called here as "sweep of temperature."

(iii) After this thermal stabilization, *I–V* curves were registered at a periodicity of 15 min until an hour after midday. These measurements are performed under a nearly constant cell temperature and a variable irradiance, and they are called here as "sweep of irradiance."

(iv) Finally, the measured characteristic points (short-circuit current, open-circuit voltage, and maximum power) have been corrected to the STC using the following equations:

$$\frac{I_{SC,SAM}}{I^*_{SC,SAM}} = \frac{I_{SC,REF}}{I^*_{SC,REF}} \quad (2)$$

$$\frac{V_{OC,SAM}}{V^*_{OC,SAM}} = \frac{V_{OC,REF}}{V^*_{OC,REF}} \quad (3)$$

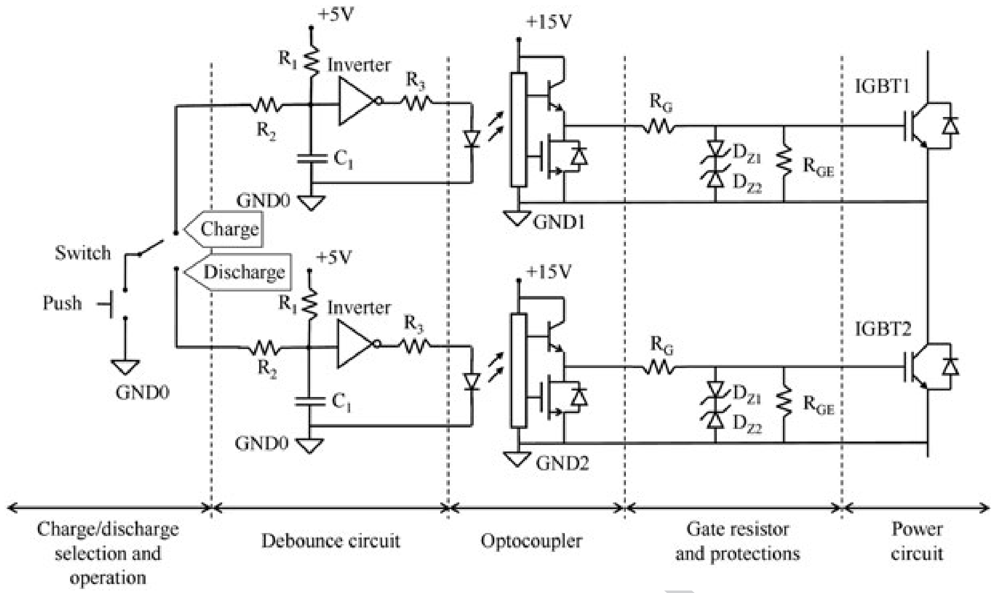

Figure 3. Control circuit. GND, ground; IGBT, insulated gate bipolar transistors.

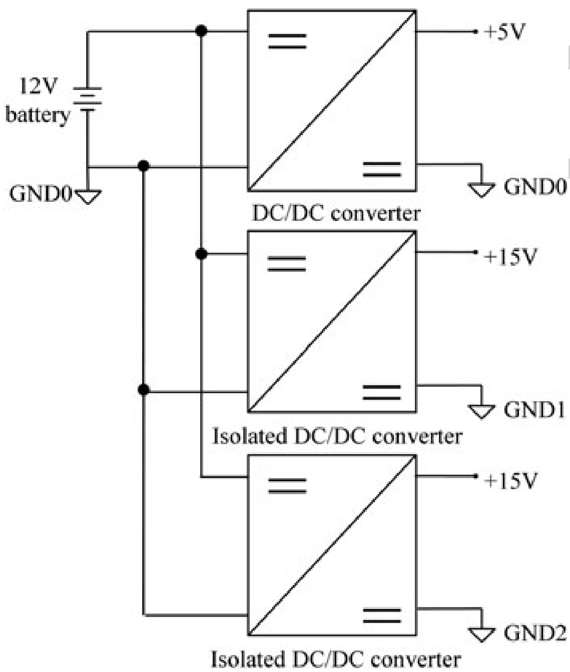

Figure 4. Supply circuit. GND, ground.

Table II. Outdoor rated PV modules at the IES-UPM.

Manufacturer	Model	Technology
Conergy	C180M	Mono x-Si
Sharp	NA-851WQ	Tandem (a-Si + μc-Si)
Solon	Solon Black 230/02	Mono x-Si
Yingly	YL-170	Poly x-Si

PV, photovoltaic.

$$\frac{P_{M,SAM}}{P^*_{M,SAM}} = \frac{P_{M,REF}}{P^*_{M,REF}} \tag{4}$$

where I_{SC} is the short-circuit current, V_{OC} the open-circuit voltage, and P_M the maximum power. Subscripts *SAM* and *REF* indicate the sample and the reference, respectively. Superscripts “*” and “blank” indicate STC and operating conditions, respectively, that exist during the test, which must be within the following limits [9]:

- clear day (diffuse fraction of global irradiance of less than 30%);
- global irradiance greater than 800 W/m^2;
- air mass (AM) between AM1 and AM2.

This sequence amounts to about 30 daily experimental points, and it has been repeated for 2 days. The operating conditions during the experiment, global irradiance, G, and cell temperature, T_C, are calculated by solving the following equations:

$$I_{SC,REF} = I^*_{SC,REF}\frac{G}{G^*}\left(1 + \alpha\left(T_C - T^*_C\right)\right) \tag{5}$$

$$V_{OC,REF} = V^*_{OC,REF}\left(1 + \beta\left(T_C - T^*_C\right)\right) \tag{6}$$

where $G^* = 1000$W/m, $T_C{}^* = 25$°C, and α and β are the temperature coefficients of the short-circuit current and the open-circuit voltage, respectively, indicated by the manufacturer in the datasheet.

Table III compares the mean and the standard deviation of the rating results of the samples obtained using Equations (2–4) with their actual calibration, whose uncertainty **T3**

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Table III. Mean and standard deviation, σ, of the deviations of the calculated parameters under STC using Equations (2)-(4) regarding their actual calibration.

PV module/material/tracking	Sweep of	G range (W/m^2)		T_C range (°C)		$I^*_{SC,SAM}$		$V^*_{OC,SAM}$		$P^*_{M,SAM}$	
		Min	Max	Min	Max	Mean (%)	σ (%)	Mean (%)	σ (%)	Mean (%)	σ (%)
Conergy mono-x-Si static	T_C	865	900	41	64	0.1	0.1	0.2	0.1	0.8	0.4
	G	921	987	64	66	0.4	0.2	0.0	0.1	0.5	0.2
Sharp a-Si + μc-Si static	T_C	801	919	33	58	−0.7	0.1	−0.5	0.2	−0.1	0.4
	G	806	994	59	64	−0.8	0.6	−0.3	0.1	−0.4	0.7
Solon mono-x-Si azimuthal	T_C	1031	1043	43	64	0.1	0.1	−0.2	0.1	−0.1	0.1
	G	950	997	55	60	−0.5	0.6	−0.6	0.4	−1.3	0.5
Yingly poly x-Si azimuthal	T_C	800	833	23	32	−0.1	0.3	0.2	0.1	0.7	0.1
	G	800	1000	31	37	−0.1	0.3	0.2	0.2	0.5	0.4

STC, standard test conditions; PV, photovoltaic.

indicated by the accredited laboratory is ±2%, ±1%, and ±2.5% for, respectively, I^*_{SC}, V^*_{OC}, and P^*_M.

The maximum relative mean deviation of the rating procedure is 1.3%, but in the rest of cases, all the relative mean deviations are within ±0.8%. And the maximum standard deviation is 0.7%, which is an excellent degree of repeatability. Finally, it is worth mentioning that there are not apparent Q10 differences ~~among~~ covering or not the PV modules, and mounting them either on trackers or on static structures.

4. CONCLUSIONS

The design of an original twin capacitive load has been described in this paper, which is used to trace simultaneously the *I–V* characteristics of two PV modules. Besides, an example of its application to the outdoor rating of PV modules has been presented, whose results show a repeatability of around 1%, which is enough to consider the on-site characterization of PV modules in the frame of quality assurance procedures.

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APPENDIX

List of Components

Component	Description and value or model
C	Aluminum electrolytic capacitors.
C_1	Capacitor 1 μF/63 V
D_1	Rectifier diode 20 A/600 V
D_2	Rectifier diode 5 A/600 V
DC/DC converter	1.0 A voltage regulator MC7805CT (+5 V)
D_{Z1}, D_{Z2}	Zener diode 18 V/1 W
F_1	Fuse 2A
F_2	Fuse 2A
IGBT1, IGBT2	Discrete IGBT SGP30N60 (30 A/600 V)
Inverter	Schmitt-trigger inverter SN74HC14
Isolated DC/DC converter	Voltage regulator TEN3-1213 (+15 V)
Optocoupler	2.0 A IGBT gate drive optocoupler HCPL3120
R_1	Resistor 1 kΩ/0.5 W
R_2	Resistor 22 Ω/0.5 W
R_3	Resistor 330 Ω/0.5 W
R_D	Power resistor 100 Ω/100 W
R_G	Resistor 10 Ω/0.5 W
R_{GE}	Resistor 47 kΩ/0.5 W
R_P	Resistor 10 Ω/10 W
V_B	Dry cell 9 V

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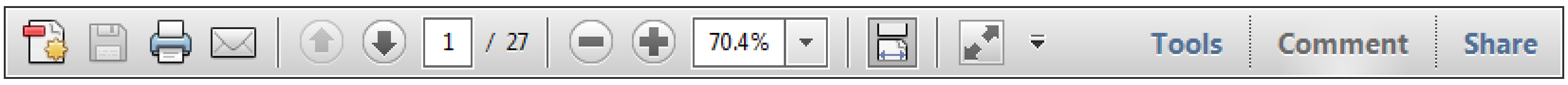

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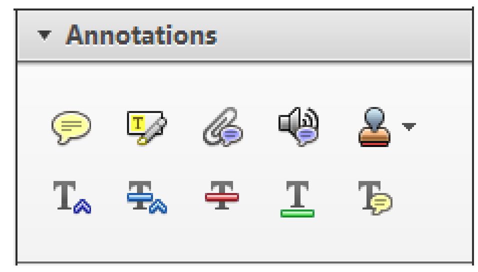

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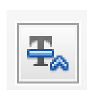

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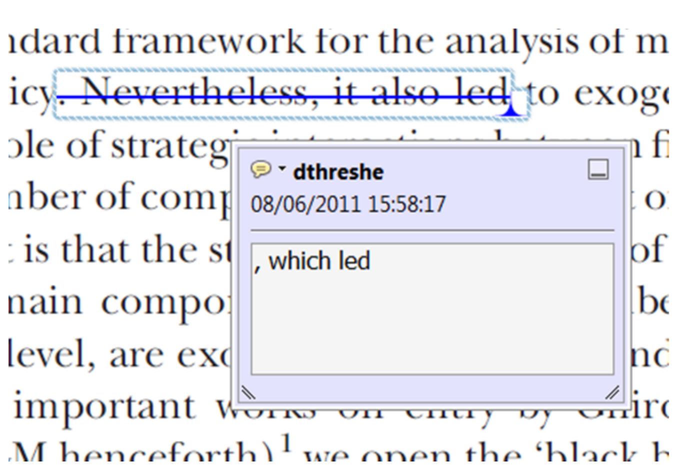

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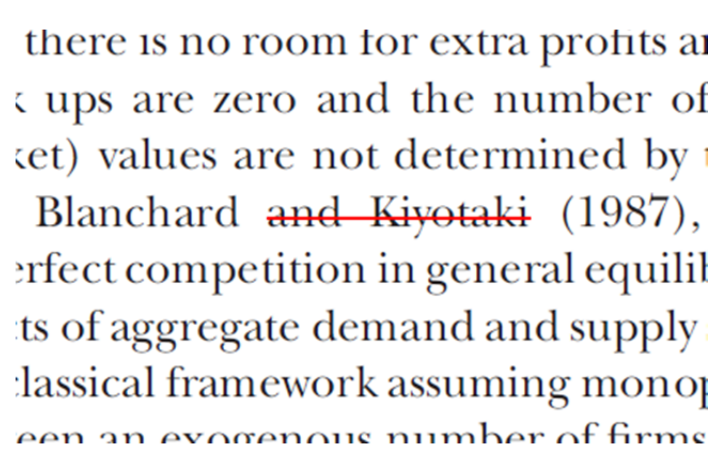

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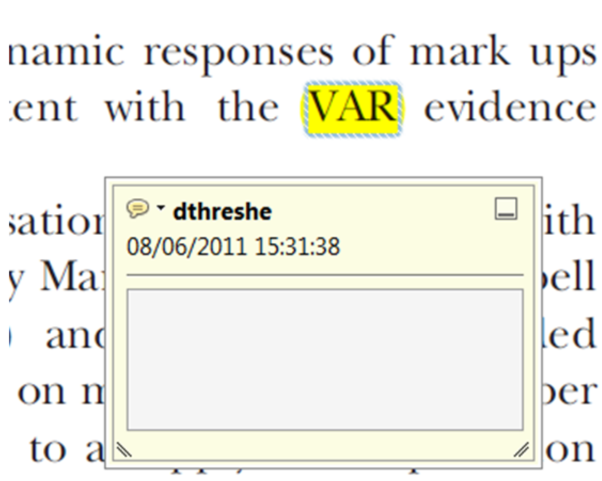

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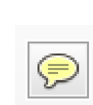

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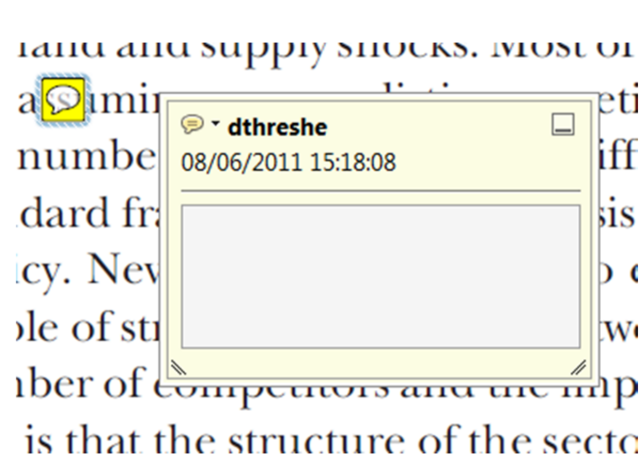

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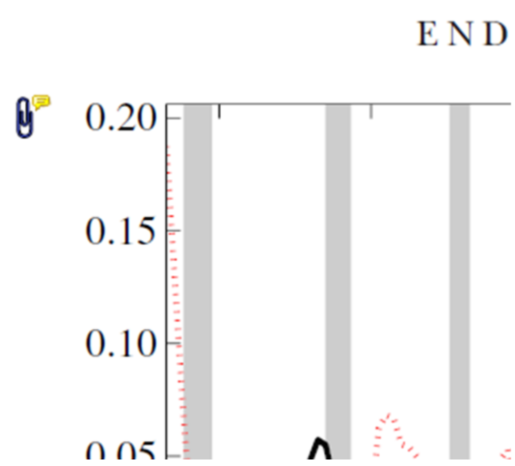
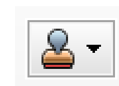
- Select the file to be attached from your computer or network.
- Select the colour and type of icon that will appear in the proof. Click OK.



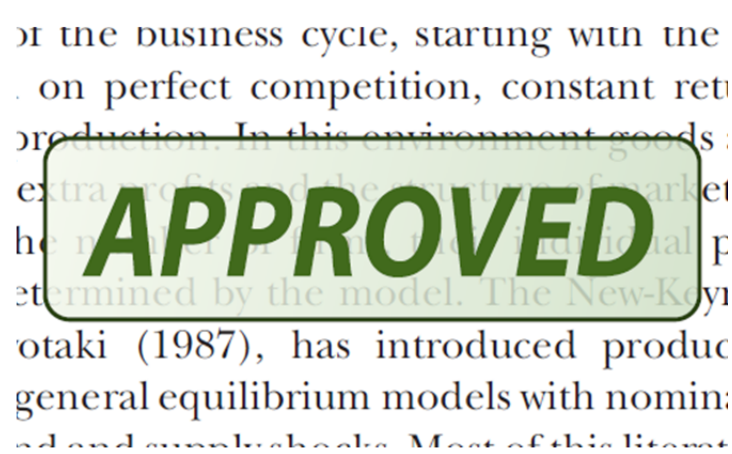
6. Add stamp Tool – for approving a proof if no corrections are required.

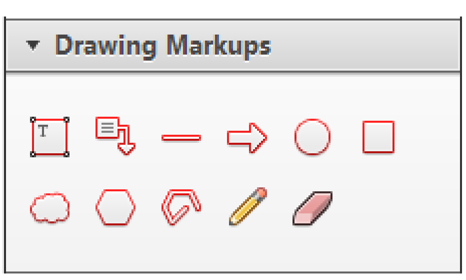


Inserts a selected stamp onto an appropriate place in the proof.

How to use it

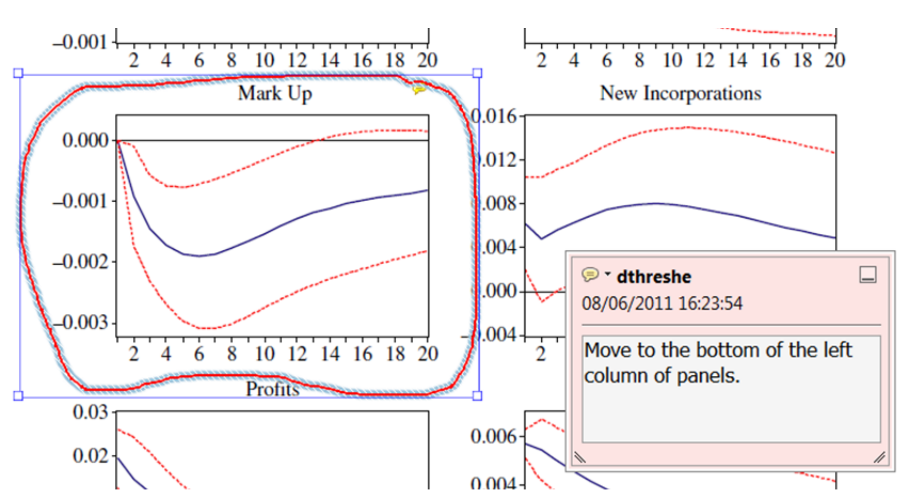
- Click on the Add stamp icon in the Annotations section.
- Select the stamp you want to use. (The Approved stamp is usually available directly in the menu that appears).
- Click on the proof where you'd like the stamp to appear. (Where a proof is to be approved as it is, this would normally be on the first page).





7. Drawing Markups Tools – for drawing shapes, lines and freeform annotations on proofs and commenting on these marks.

Allows shapes, lines and freeform annotations to be drawn on proofs and for comment to be made on these marks..



How to use it

- Click on one of the shapes in the Drawing Markups section.
- Click on the proof at the relevant point and draw the selected shape with the cursor.
- To add a comment to the drawn shape, move the cursor over the shape until an arrowhead appears.
- Double click on the shape and type any text in the red box that appears.

For further information on how to annotate proofs, click on the Help menu to reveal a list of further options: